

# Testing the special relativity theory with neutrino interactions

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**Abstract** – A recent measurement of neutrino velocity by the OPERA experiment and prediction of energy loss of superluminal neutrino via the pair creation process  $\nu \rightarrow \nu e^+ e^-$  stimulated a search of isolated  $e^+ e^-$  pairs in detectors with good tracking capability traversed by a large flux of high energy neutrino like NOMAD. NOMAD has already searched for similar topologies. These results can be reinterpreted to provide stringent limits on special relativity violating parameters separately for each  $\nu$  species.

**Introduction.** – The measurement of  $\nu$  velocity recently [1] reported by the OPERA experiment stimulated theoretical studies [2] (see also [3, 4]) about the consequence of  $\nu$  superluminality<sup>1</sup>.

They predict that that a superluminal  $\nu$  would loose energy through Cerenkov-like processes like

$$\nu_\mu \rightarrow \begin{cases} \nu_\mu + \gamma & (a) \\ \nu_\mu + \nu_e + \bar{\nu}_e & (b) \\ \nu_\mu + e^+ + e^- & (c) \end{cases} \quad (1)$$

The main effective process of energy loss is expected to be (c), that has a threshold  $E_0 = 2m_e c^2 / \sqrt{\delta_\nu}$ , where  $m_e c^2$  is the electron rest energy and  $\delta_\nu = \beta_\nu^2 - 1 \approx 2 \times (\beta_\nu - 1)$ . [2, 3] report that the rate of pair emission and rate of energy loss are

$$\Gamma = k' \frac{G_F^2}{192\pi^3} E_\nu^5 \delta_\nu^3 \quad (2)$$

$$\frac{dE}{dx} = -k \frac{G_F^2}{192\pi^3} E_\nu^6 \delta_\nu^3 \quad (3)$$

where  $k = 25/448$  and  $k' = 1/14$  are numerical constants,  $G_F$  is the Fermi constant of weak decay,  $E_\nu$  the neutrino energy. From Eq.3 the average fractional energy loss is

$$\frac{1}{E} \frac{dE}{dx} \frac{1}{\Gamma} = -\frac{k}{k'} \approx 0.78 \quad (4)$$

**Energy cutoff.** – Eq.3 can be integrated, assuming  $\delta_\nu$  independent from the energy, to obtain that a  $\nu$  with

<sup>1</sup>Results presented at Neutrino 2012 conference in Kyoto, Japan by the OPERA, LVD, ICARUS, Borexino, T2K and MINOS collaborations (see also [5]) rule out the original OPERA claim and are consistent with the neutrinos moving at the speed of light within  $\sim 10^{-6}$ .

initial energy  $E_0$  after traveling a distance  $L$  will have energy  $E$

$$E^{-5} - E_0^{-5} = 5k\delta_\nu^3 \frac{G_F^2}{192\pi^3} L \equiv E_T^{-5} \quad (5)$$

$E_T$  acts as a spectral cutoff, therefore for any value of  $\delta_\nu$  the high energy spectrum of a neutrino beam would be depleted over a sufficiently long path.

The absence of such cutoff at ICARUS [6] at LNGS ( $L \approx 730$  km) up to above 50 GeV and at NOMAD [7, 8] ( $L \approx 1$  km) above 200 GeV allows to set limits  $\delta_\nu \leq 5 \times 10^{-6}$ . Another effect that would deplete the  $\nu$  distribution at high energy is the  $\pi$  decay kinematics. The phase space for the decay  $\pi \rightarrow \mu \nu_\mu$  for superluminal  $\nu_\mu$  becomes smaller and smaller with increasing  $\pi$  energy; the effect is reducing the flux of high energy  $\nu$  down to zero above some threshold [4, 9].

As noted in [2, 3], that contradicts measurements of high energy neutrino interactions in underground detectors. The most stringent limits can be derived analyzing [3] high energy atmospheric  $\nu_\nu$  ( $\bar{\nu}_\mu$ ) detected in underground detectors [10].

An alternative approach is to look for the production of isolated  $e^+ e^-$  pairs in neutrino detectors traversed by a high energy, high intensity neutrino flux such as the NOMAD detector [11].

**The NOMAD detector.** – The NOMAD detector was designed for searching  $\nu_\mu \rightarrow \nu_\tau$  oscillation at the CERN West Area Neutrino Facility (WANF) beam line. The detector includes an active target of drift chambers (DC) with a mass of 2.7 tons and a volume  $\approx 2.6 \times 2.6 \times 4$  m<sup>3</sup> complemented with electron identification provided by a Transition Radiation Detector (TRD)

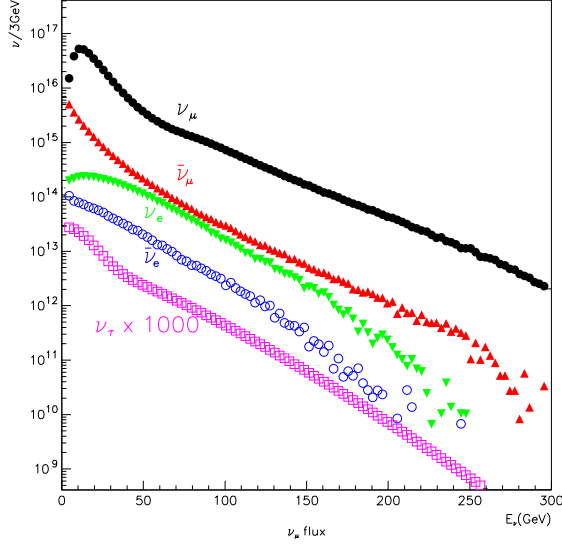


Fig. 1: Prediction of undistorted spectra of the different  $\nu$  species crossing NOMAD ( $\nu_\tau$  is multiplied with 1000 for visibility) with the 1996-1998 data set ( $4.1 \cdot 10^{19}$  p.o.t.)

and an Electromagnetic Calorimeter (ECAL). This detector has proved effective in search of  $\nu$  interaction with only one or few photons in the exclusive final state [12–14]. The topology of these events is one or more  $e^+e^-$  pairs originating in the target.

**The neutrino beam.** – The neutrino beam impinging on the NOMAD detector originates from the CERN West Area Neutrino Facility (WANF) [15]; it is described in detail in [7]. The results are summarized in Fig.1 that shows the undistorted ( $\delta_\nu = 0$ ) total neutrino fluxes, subdivided in the different components, traversing the active area of the NOMAD detector ( $\approx 2.6 \times 2.6 \text{ m}^2$ ) during the period 1996-1998 for a total of  $4.1 \cdot 10^{19}$  protons on target. The  $\nu_\tau$  component, deduced from [16], is supposed to equal the  $\bar{\nu}_\tau$  component.

**The  $e^+e^-$  pair spectrum in NOMAD.** – The spectral forms of the  $e^+e^-$  pairs produced over a 4.0 m length in the NOMAD detector are affected for  $\delta_\nu \geq 10^{-6}$  by  $\nu$  spectral distortion and for  $\delta_\nu \leq 10^{-9}$  by threshold effects. For intermediate values the spectra simply scale proportionally to  $\delta_\nu^3$ . The different spectral components according to Eq.3 are shown in Fig.2 for  $\delta_\nu = 0.5 \times 10^{-6}$ , a representative value of the scaling region. In order to ease a comparison with existing experimental data, the fluxes have been multiplied by an average detection efficiency  $\epsilon = 0.26$  deduced by [12].

The most appropriate comparison with existing NOMAD data is [12], where  $e^+e^-$  pairs from decay of a heavy neutrino mixing with  $\nu_\tau$  were searched. This search established that the number of  $e^+e^-$  pairs is compatible with the expectations and additional sources can contribute no

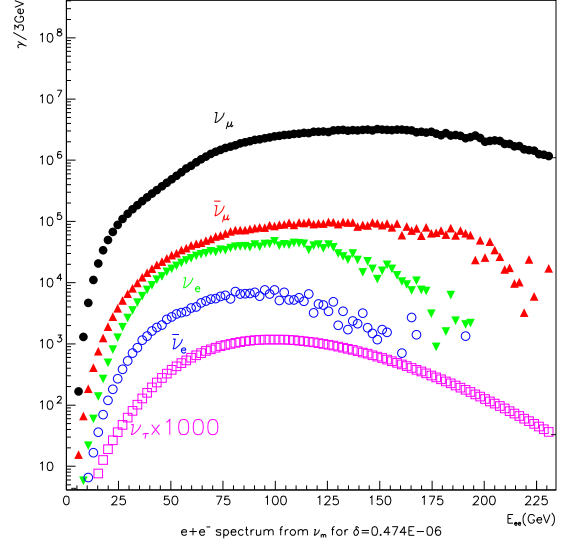


Fig. 2: Spectra of the  $e^+e^-$  pairs produced by the different  $\nu$  species in NOMAD ( $\nu_\tau$  is multiplied with 1000 for visibility) with the 1996-1998 data set ( $4.1 \cdot 10^{19}$  p.o.t.) accounting for spectral distortion caused by  $\nu$  energy loss and for  $\delta_\nu = 0.5 \times 10^{-6}$ . An average detection efficiency  $\epsilon = 0.26$  is included.

more than  $\mathcal{O}(1)$  events.

**Limits on  $\delta_\nu$ .** – The integrated  $e^+e^-$  fluxes  $F_{e^+e^-}$  ( $\delta_\nu = 0.5 \times 10^{-6}$ ) for each species in the detector from Fig.2 are in the second column of Tab.1, while in the last column there are the values of  $\delta_\nu$  for which one  $e^+e^-$  pair is predicted. The last column is calculated accounting for distortion and threshold effects as shown in Fig.3, but it follows very closely the scaling law from Eq.3,  $\delta_\nu = 0.5 \times 10^{-6} / F_{e^+e^-}^{1/3}$ .

We emphasize that the limits derived with this analysis are approximate: the efficiency from [12] is relative to a different (softer)  $e^+e^-$  energy range, the spectrum of the process Eq.1c is assumed monochromatic and the statistical analysis is very crude. A dedicated analysis should be performed by the NOMAD collaboration to obtain more precise limits.

Existing limits are  $\delta_{\nu_e} < 4.0 \cdot 10^{-9}$  from SN1987 [17] and  $\delta_{\nu_\mu} < 1.4 \cdot 10^{-8}$  [2]; in [2] stronger limits from high energy events in IceCube are also presented for an unspecified  $\nu$  species. Recently, following an approach similar to that presented in this paper, the ICARUS collaboration set the limit  $\delta < 2.5 \cdot 10^{-8}$  [6], presumably to be applied to  $\nu_\mu$ .

The limit in Tab.1 is the only one up to date on  $\delta_{\nu_\tau}$ . Following [18] we remark that these limits are valid for the extensions of the special relativity theory with a so called 'broken' Lorentz invariance, for which the processes in Eq.1 take place; alternative extensions of the theory with a so called 'deformed' Lorentz invariance, do not predict these processes and are not constrained by this

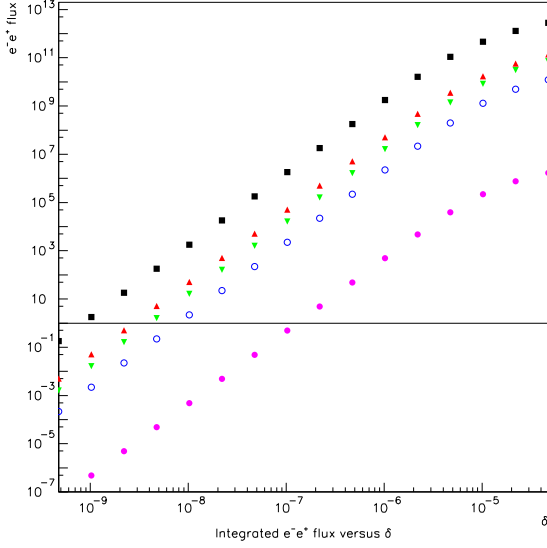


Fig. 3:  $e^+e^-$  flux versus  $\delta_\nu$  for the various  $\nu$  species (colors and symbols are those used in Fig.2). An average detection efficiency  $\epsilon = 0.26$  is included. The horizontal line corresponding to 1  $e^+e^-$  pair defines the approximate upper limit.

analysis. Neither the possibility of a tachyonic superluminal neutrino is constrained by this analysis; nevertheless the discussions in [19,20] stress the difficulty of reconciling the data from accelerator experiments with this interpretation.

**Conclusions.** — We set strong bounds on special relativity violating processes involving neutrinos and anti-neutrinos of all species based on previous searches of isolated  $e^+e^-$  pairs in the NOMAD detector. This translates in strong limits on possible superluminal behaviours of neutrinos of all species for extensions of the special relativity theory with 'broken' Lorentz invariance. We strongly encourage the NOMAD collaboration to perform a dedicated analysis to optimize these limits.

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## REFERENCES

- [1] ADAM T. *et al.*, *Measurement of neutrino velocity with the OPERA detector in the CNGS beam* arXiv:1109.4897 [hep-ph].
- [2] COHEN A. G. and GLASHOW S. L., *Phys. Rev. Lett.* **107**, **2011** (181803) arXiv:1109.6562 [hep-ph].
- [3] BI X. J., P.F. YIN Z. H. Y. and YUAN Q., *Phys. Rev. Lett.* **107**, **2011** (241802) arXiv:1109.6667 [hep-ph].

Table 1: Total  $e^+e^-$  pairs expected for  $\delta_\nu = 0.5 \times 10^{-6}$  for each species and  $\delta_\nu$  giving one  $e^+e^-$  pair.

$\nu$ species	$F_{e^+e^-}$	$\delta_\nu$
$\nu_\mu$	$1.8 \times 10^8$	$8.4 \times 10^{-10}$
$\bar{\nu}_\mu$	$5.1 \times 10^6$	$2.7 \times 10^{-9}$
$\nu_e$	$1.6 \times 10^6$	$4.0 \times 10^{-9}$
$\bar{\nu}_e$	$2.2 \times 10^5$	$7.8 \times 10^{-9}$
$\nu_\tau (\bar{\nu}_\tau)$	$4.8 \times 10^1$	$1.3 \times 10^{-7}$

- [4] GONZALES-MESTRES L., *Astrophysical consequences of the opera superluminal neutrino* arXiv:1109.6630 [hep-ph].
- [5] ANTONELLO M. *et al.*, *Measurement of the neutrino velocity with the ICARUS detector at the CNGS beam* arXiv:1203.3433 [hep-ph].
- [6] ANTONELLO M. *et al.*, *Phys. Lett. B* **711**, **2012** (270) arXiv:1110.3763 [hep-ph].
- [7] ASTIER P. *et al.*, *Nucl. Instrum. & Meth. A* , **515** (2003) 800.
- [8] LYUBUSHKIN V. *et al.*, *Eur. Phys. J. C* **63**, **2009** (355) arXiv:0812.4543 [hep-ph].
- [9] COWSIK R., NUSSINOV S. and SARKAR U., *Phys. Rev. Lett.* **107**, **2011** (251801) arXiv:1110.0241 [hep-ph].
- [10] ABBASI R. *et al.*, *Phys. Rev. D* **83**, **2011** (012001) arXiv:1010.3980 [hep-ph].
- [11] ALTEGOER J. *et al.*, *Nucl. Instrum. & Meth. A* , **404** (1998) 96.
- [12] ASTIER P. *et al.*, *Phys. Lett. B* , **506** (2001) 27.
- [13] ASTIER P. *et al.*, *Phys. Lett. B* , **527** (2002) 23.
- [14] ASTIER P. *et al.*, *Phys. Lett. B* , **483** (2000) 371.
- [15] ACQUISTASPACE G. *et al.*, CERN-ECP/95-14 (1995).
- [16] DE VYVER B. V., *Nucl. Instrum. & Meth. A* , **385** (1997) 91.
- [17] LONGO M. J., *Phys. Rev. D.* , **36** (1987) 3276.
- [18] AMELINO-CAMELIA G., FRIEDEL L., KOWALSKI-GLIKMAN J. and SMOLIN L., *Mod.Phys.Lett. A* **27**, **2012** (1250063) arXiv:1110.0521 [hep-ph].
- [19] AMELINO-CAMELIA G. *et al.*, *Int.J.Mod.Phys. D* **20**, **2011** (2623) arXiv:1109.5172 [hep-ph].
- [20] DRAGO A. *et al.*, *Europhys.Lett.* **97**, **2012** (21002) arXiv:1109.5917 [hep-ph].